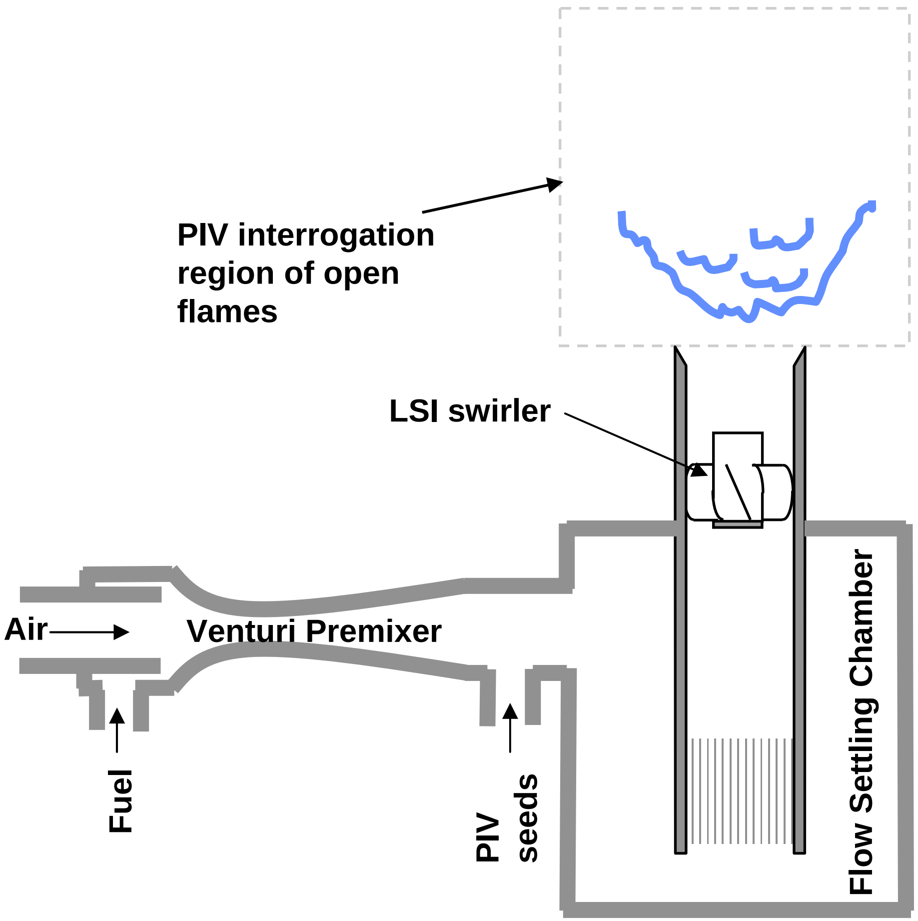
Obtaining an Analytical Model for Low-swirl Combustion

- **Apply Particle Imaging Velocimetry (PIV) to measure instantaneous velocity vectors within an area of 13 x 13 cm**
  - **Facilitates the collection of a large amount of flowfield data**
- **Characterize flowfield and flame behavior as function of:**
  - **swirl number**
  - **fuel type**
  - **fuel air ratio**
  - **bulk flow velocity**
- **Define key parameters that characterize the flowfield**
- **Develop analytical model for the relationships between the flame and flowfield**
  - **Basis for scaling and adaptation guidelines**
  - **Less reliance on computational fluid mechanics (CFD)**
  - **Reduce uncertainties and increase predictability**

Apparatus, Diagnostics & Analysis

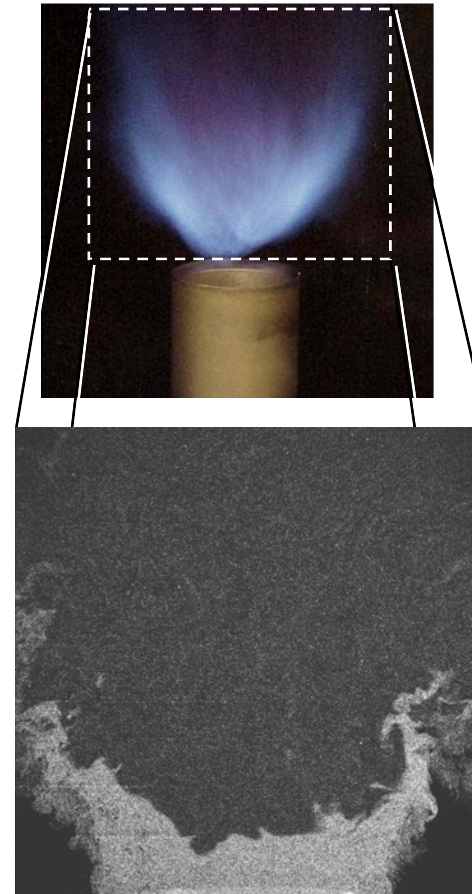


- LSI mounted to the plenum and premixer of an industrial burner
- Applied PIV to atmospheric open flames
  - Previous development with Solar demonstrated relevancy of open flame experiments
- Deduced mean, rms velocities, Reynolds stresses & turbulent flame speeds

Experimental Conditions

- Lean flames burning single and dual-component fuels with a range of Wobbe indices
- Operating regimes for each fuel defined by LBO and emissions
- Varied bulk flow velocity U_0 from 7 to 22 m/s

Fuel Composition	T_{ad} at ϕ = 1 K	S_L at ϕ = 1 m/s	S_L at T_{ad} = 1800K
CH_4	2230	0.39	0.17
C_2H_4	2373	0.74	0.23
C_3H_8	2253	0.45	0.22
0.5 CH_4/ 0.5 CO_2	2013	0.20	0.12
0.6 CH_4/ 0.4 N_2	2133	0.31	0.16
0.6 CH_4/ 0.4 H_2	2258	0.57	0.22
H_2	2535	2.4	0.61
0.5 H_2/ 0.5 N_2	2056	1.2	0.61

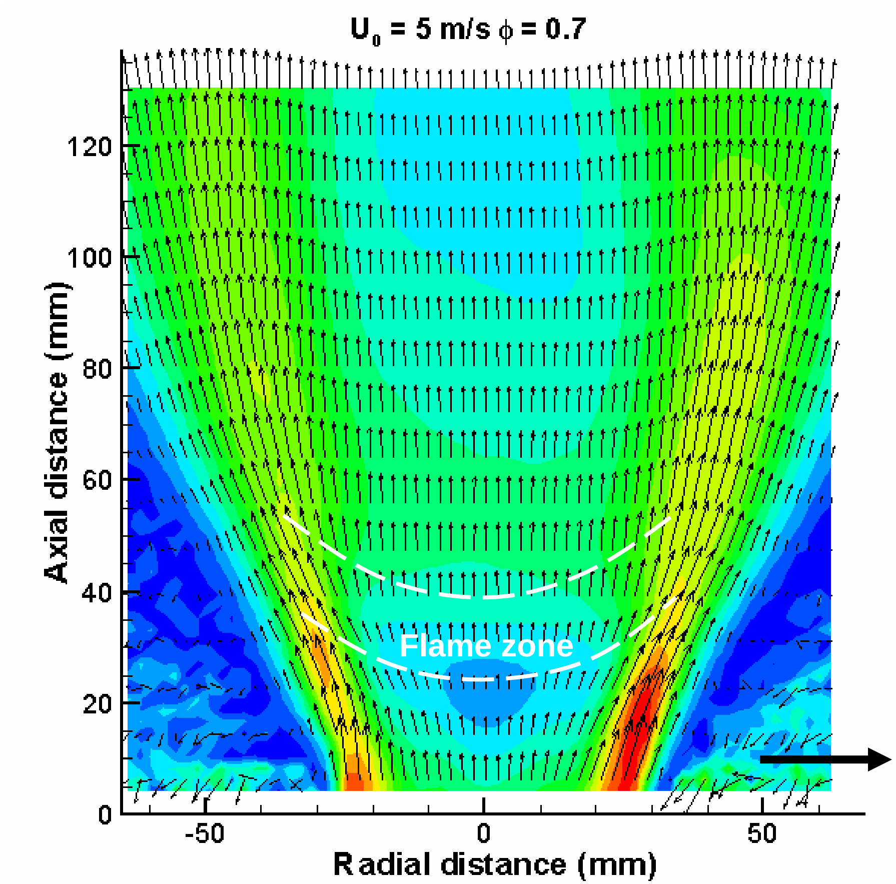


Raw PIV image showing wrinkled premixed turbulent flame structures

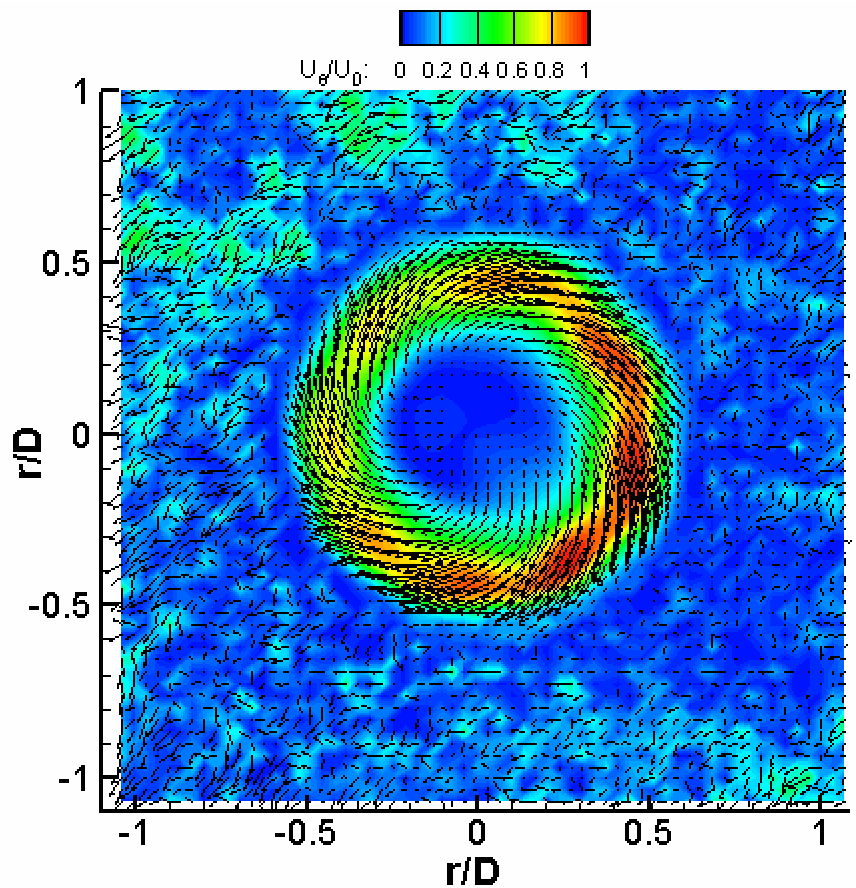
Hydrocarbon Flame Results

Flowfield of LSC Shown by Particle Image Velocimetry

- **Mean velocity vectors on axial plane**



- **Mean velocity vectors on cross-plane**



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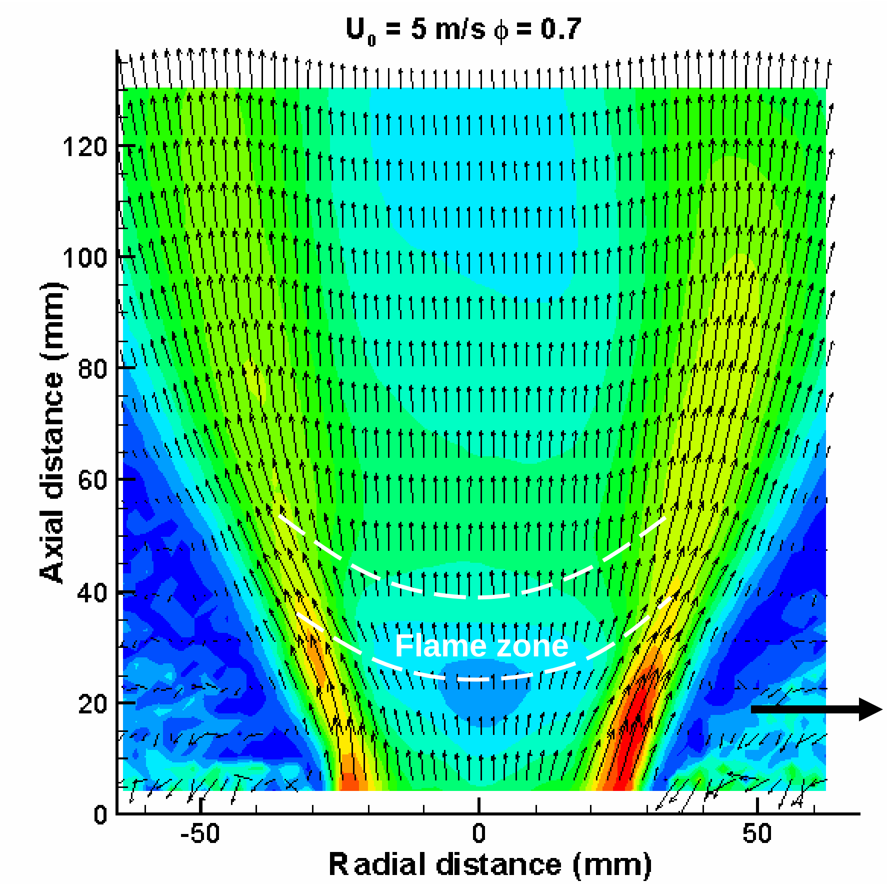

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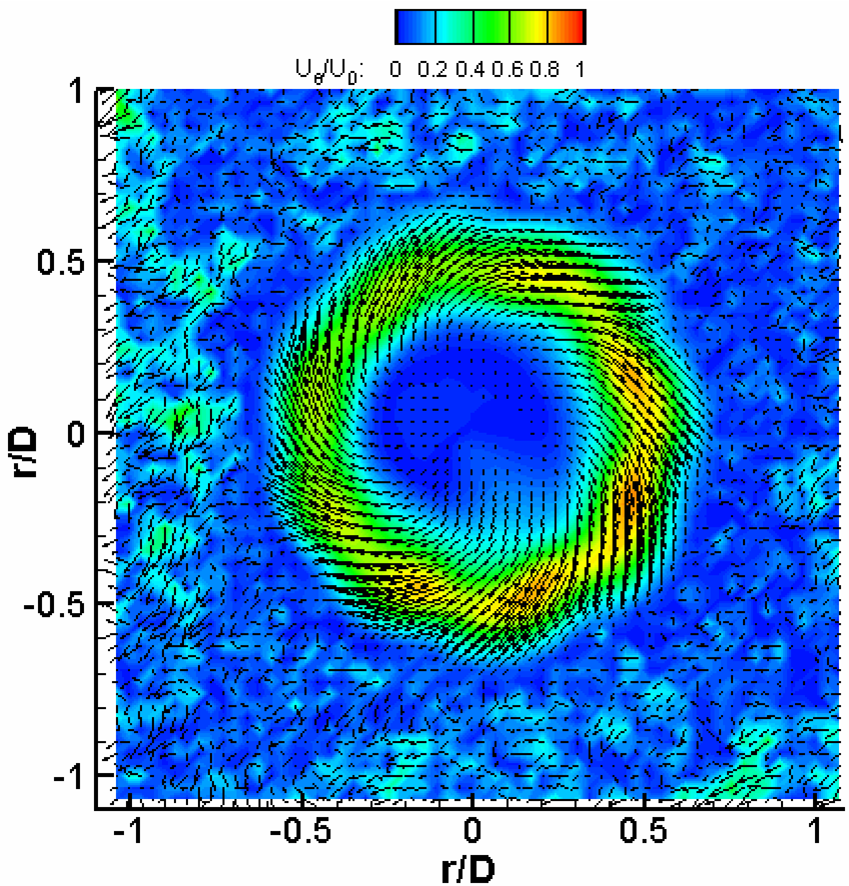

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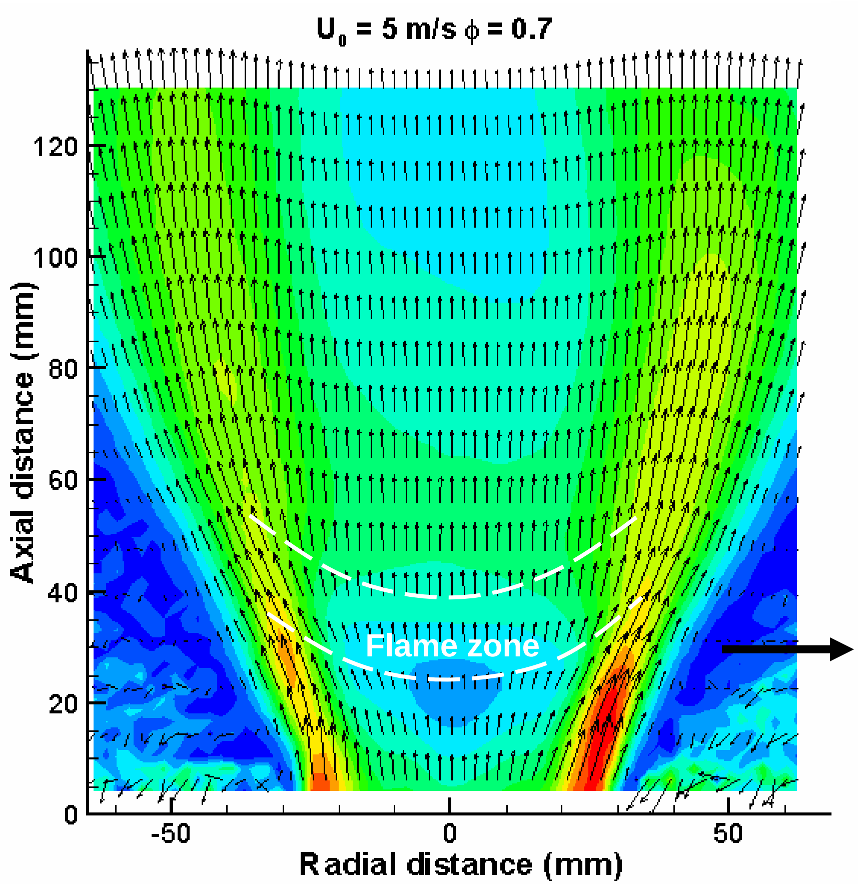

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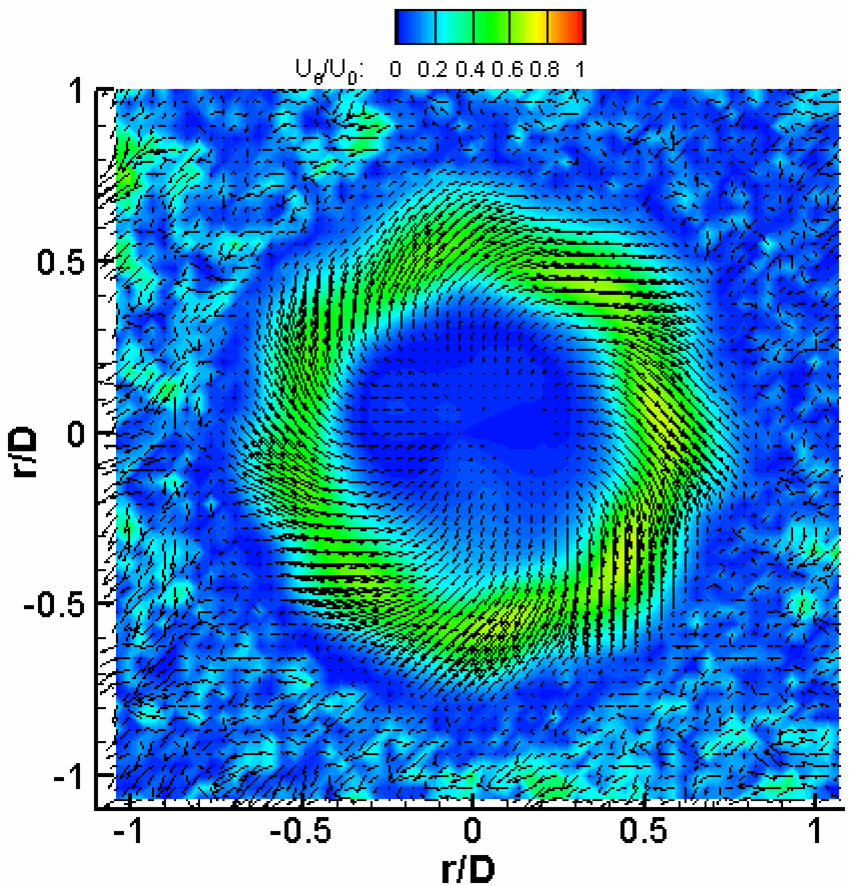

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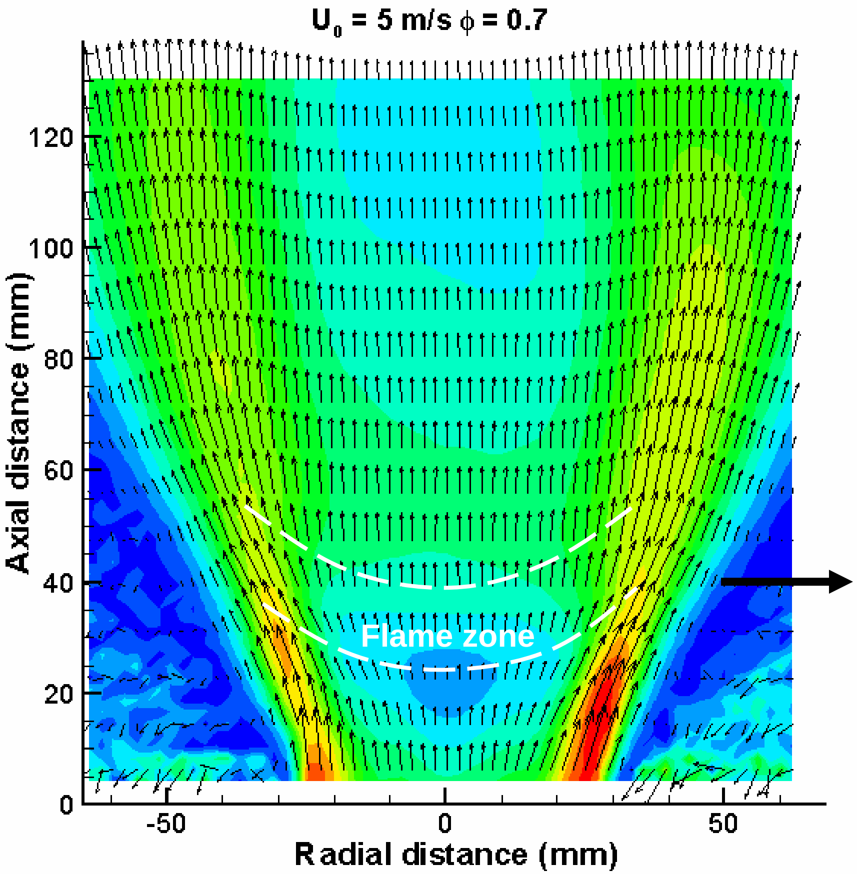

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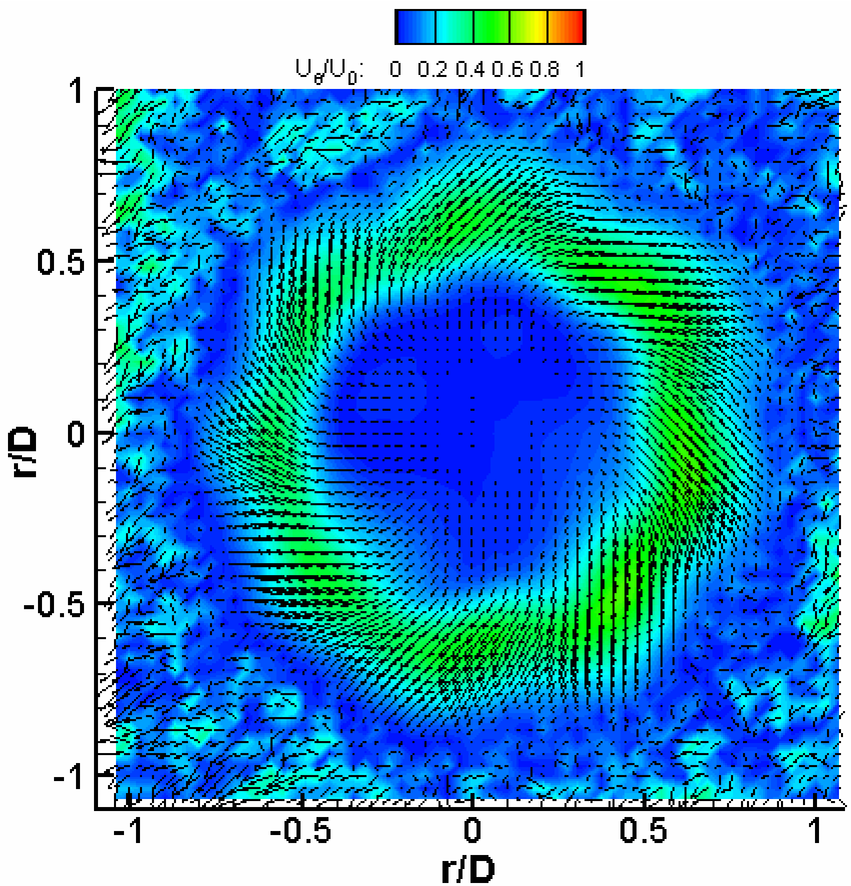
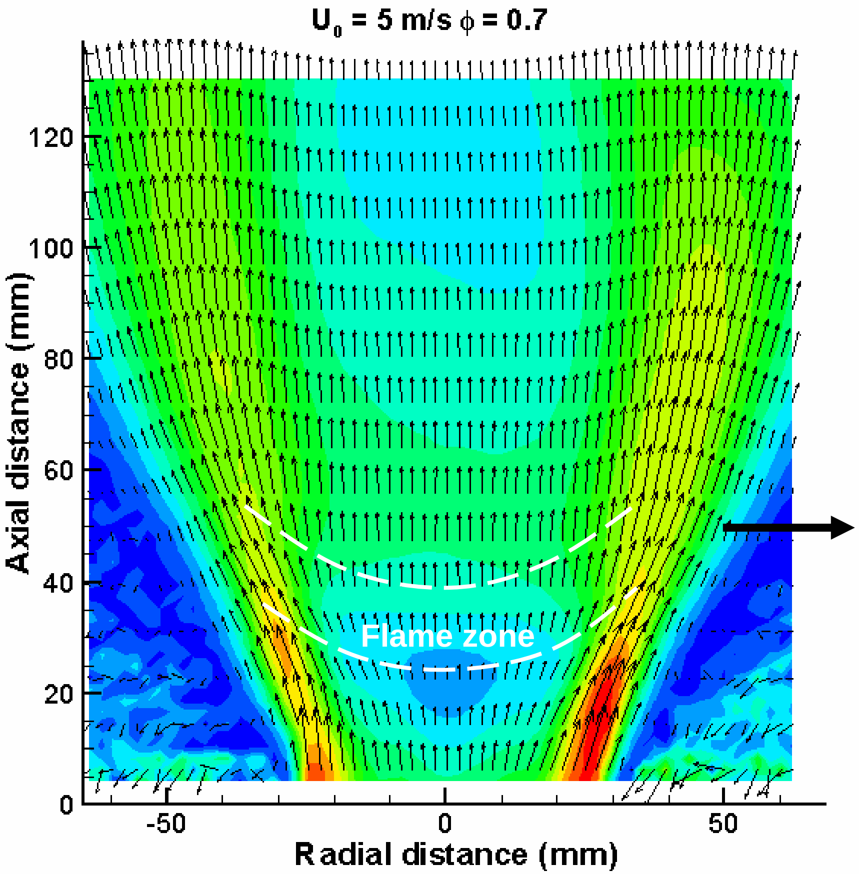


Flowfield of LSC Shown by Particle Image Velocimetry

- **Mean velocity vectors on axial plane**



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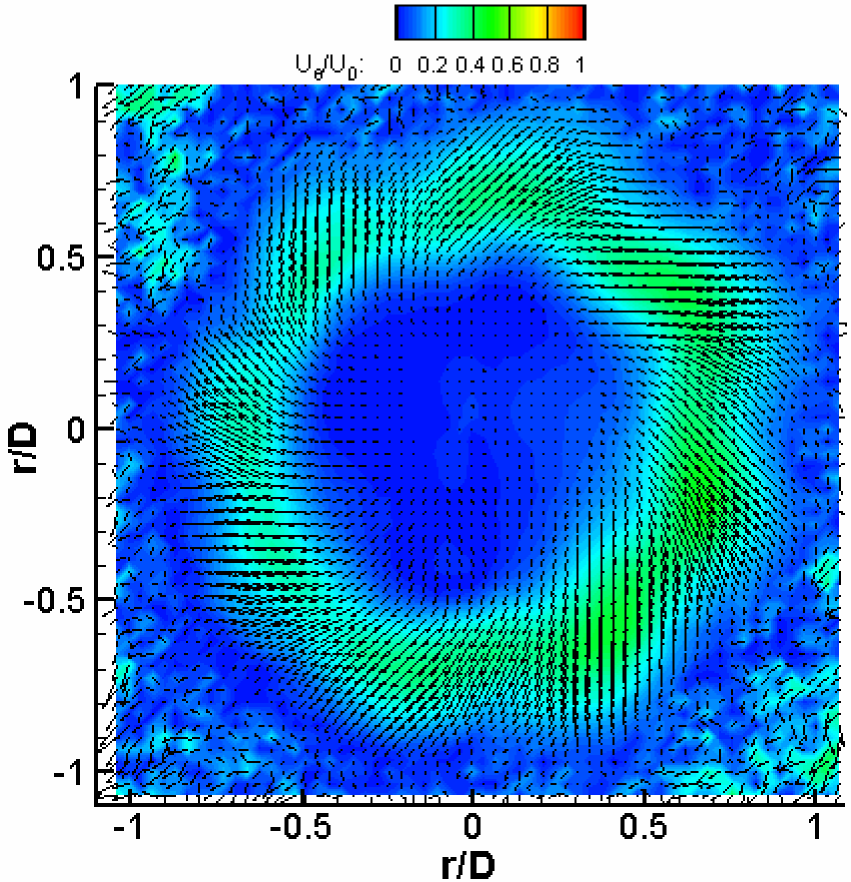

Flowfield of LSC Shown by Particle Image Velocimetry

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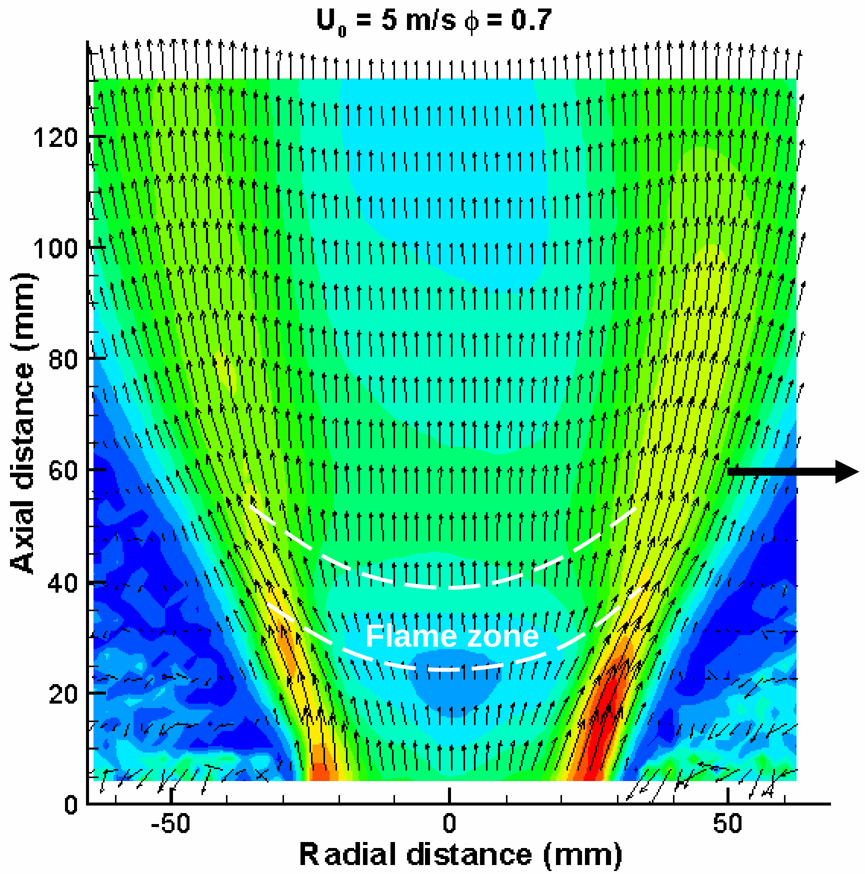

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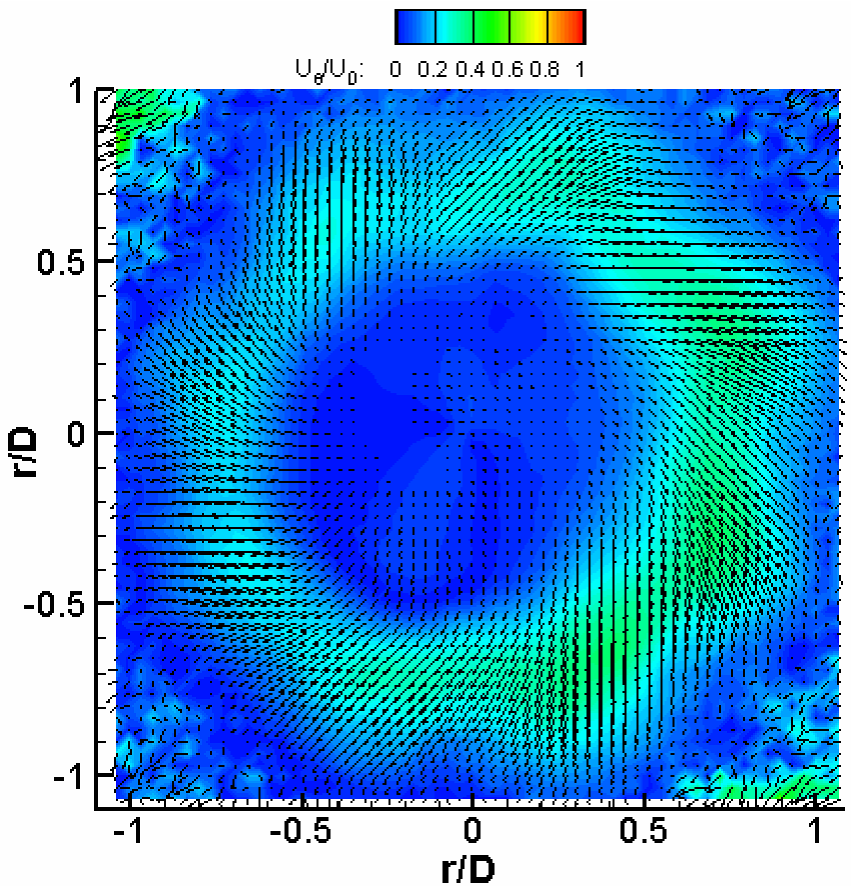
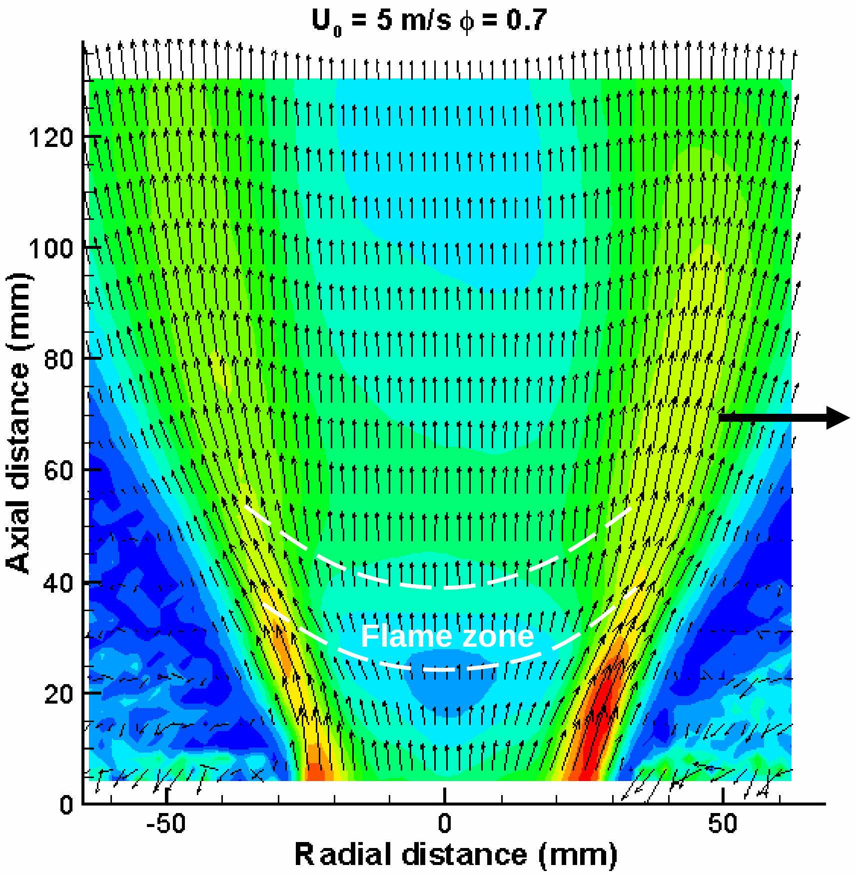
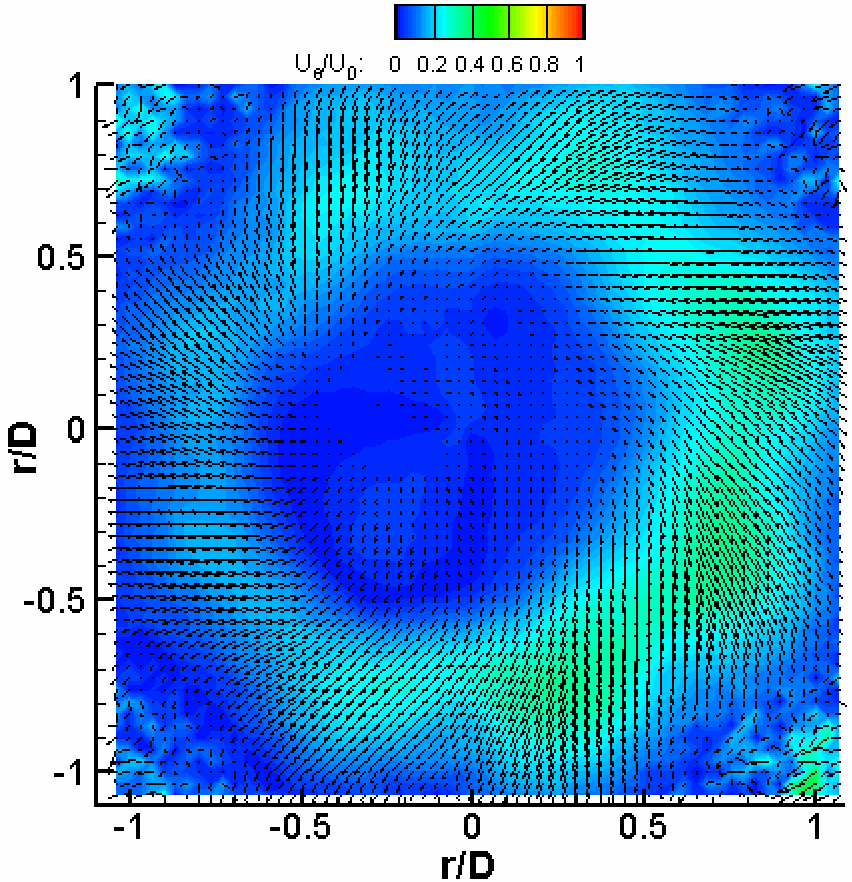


Flowfield of LSC Shown by Particle Image Velocimetry

- Mean velocity vectors on axial plane

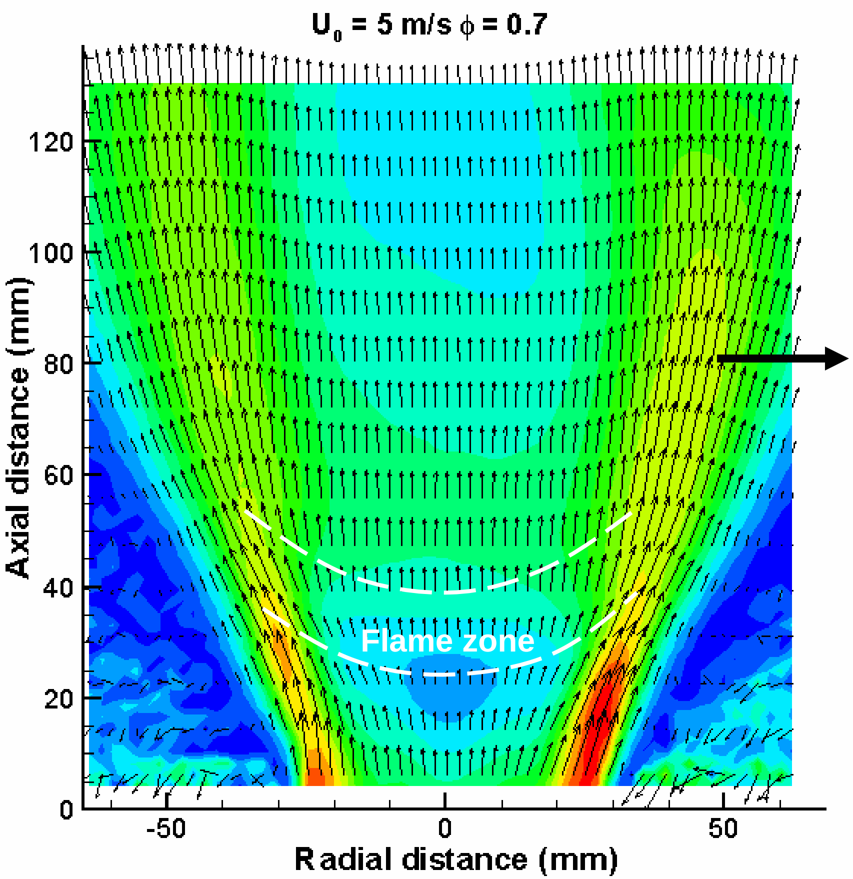


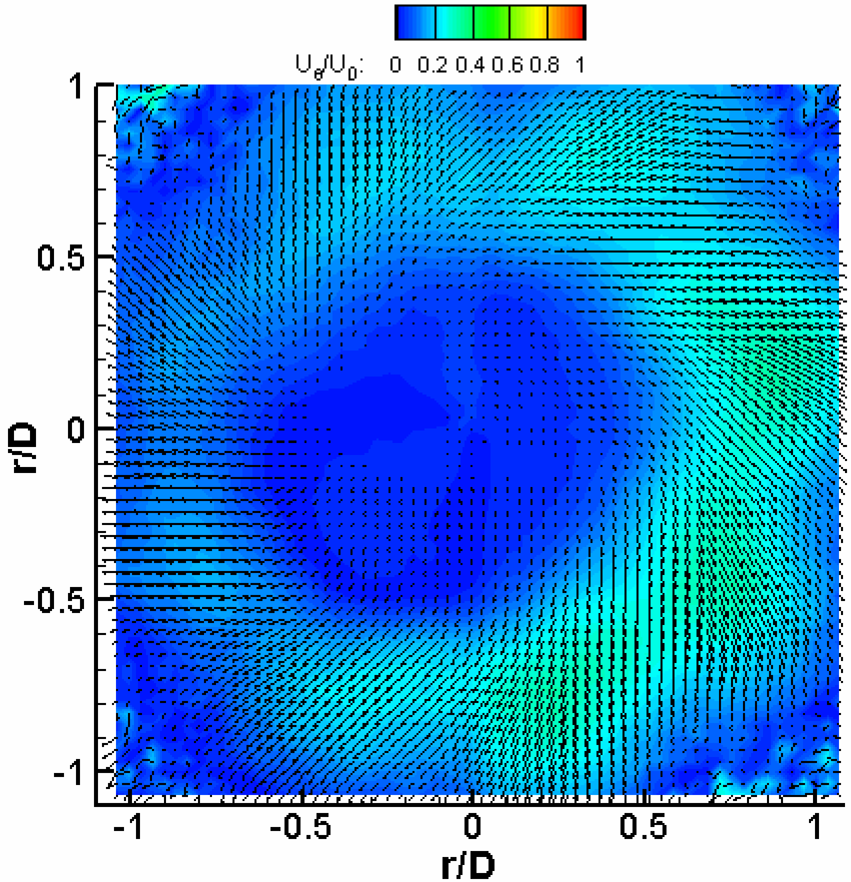
- Mean velocity vectors on cross-plane



Flowfield of LSC Shown by Particle Image Velocimetry

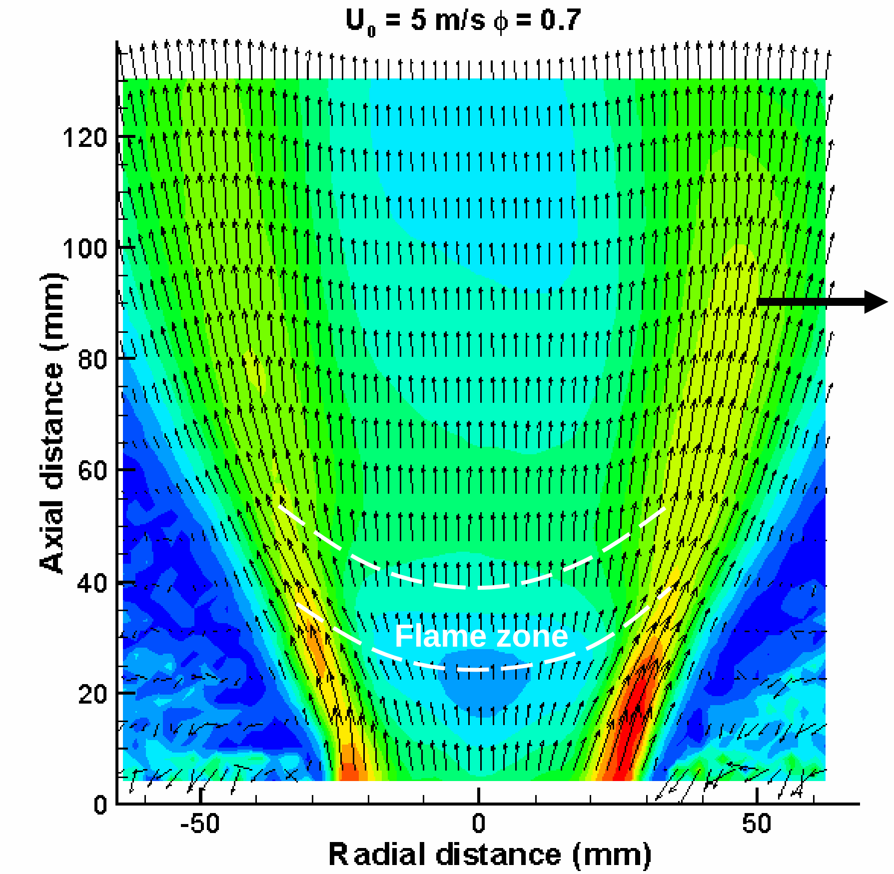
- Mean velocity vectors on axial plane
- Mean velocity vectors on cross-plane



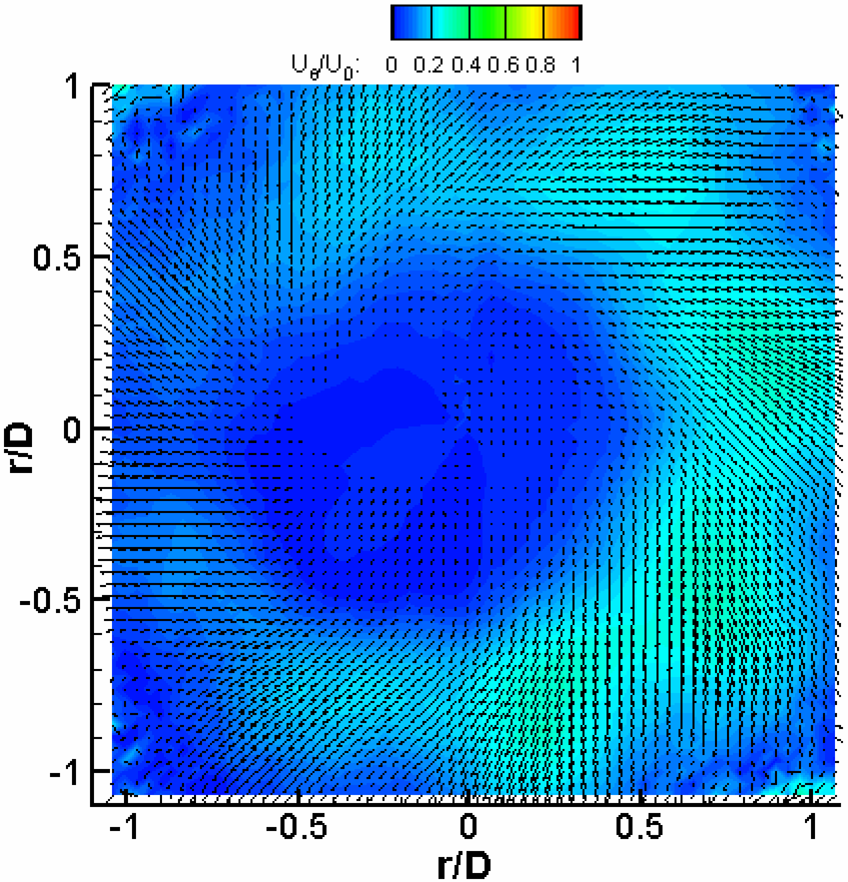


Flowfield of LSC Shown by Particle Image Velocimetry

- **Mean velocity vectors on axial plane**

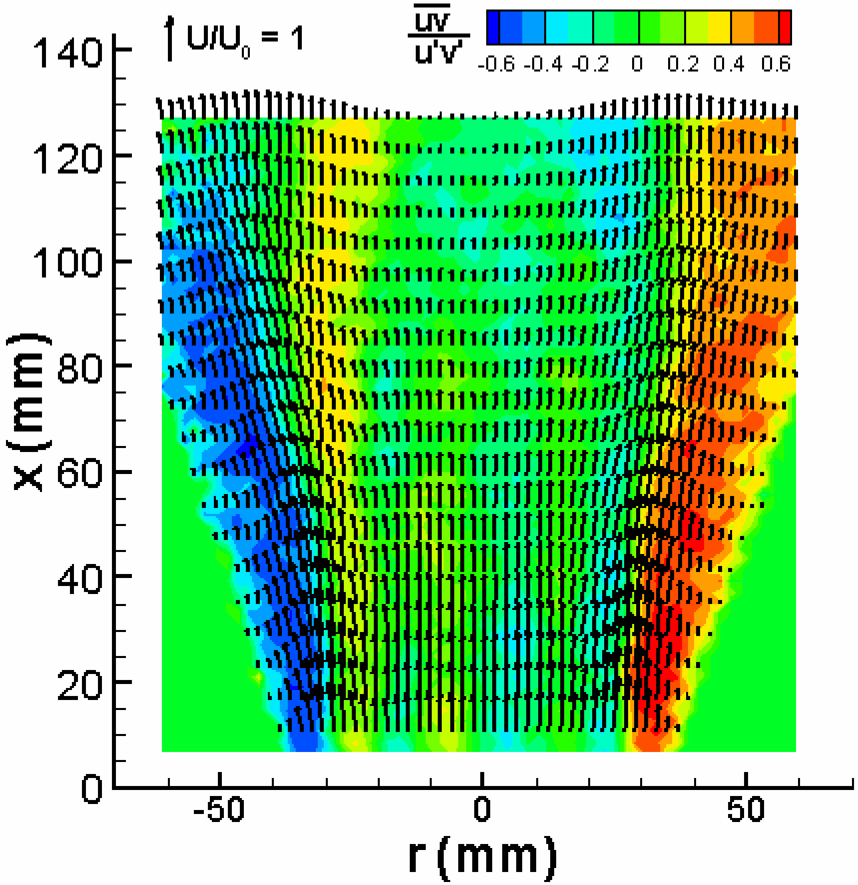


- **Mean velocity vectors on cross-plane**

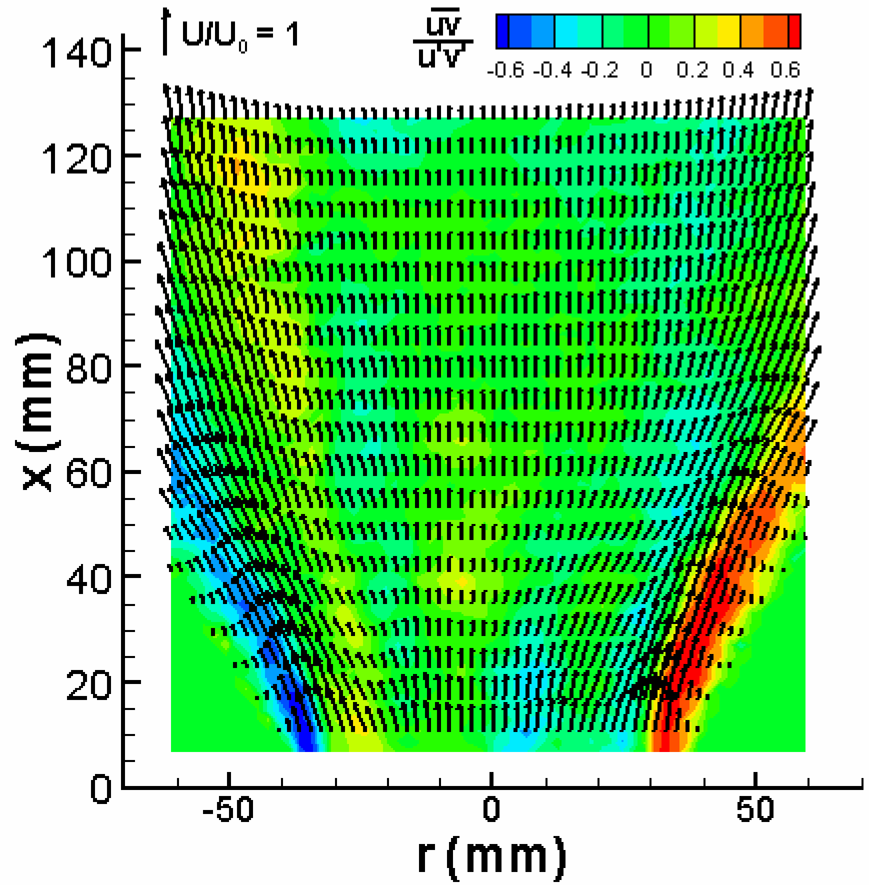


Normalized mean vectors and Reynolds stress at U_0 = 7 m/s

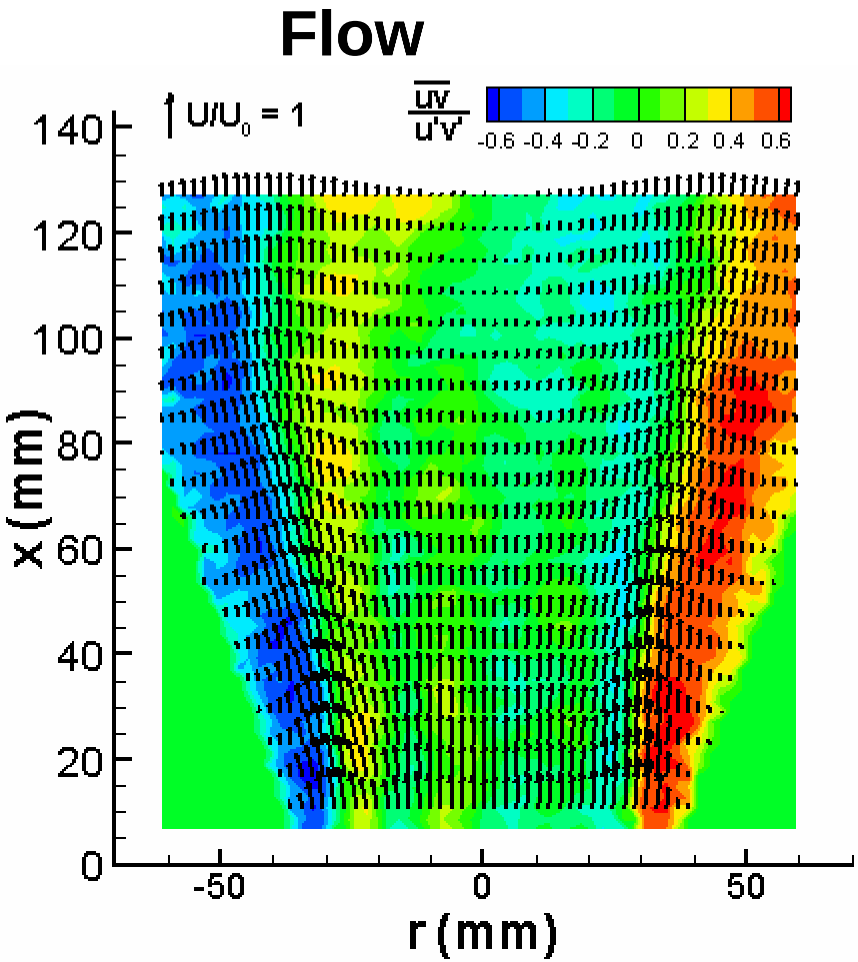
Flow

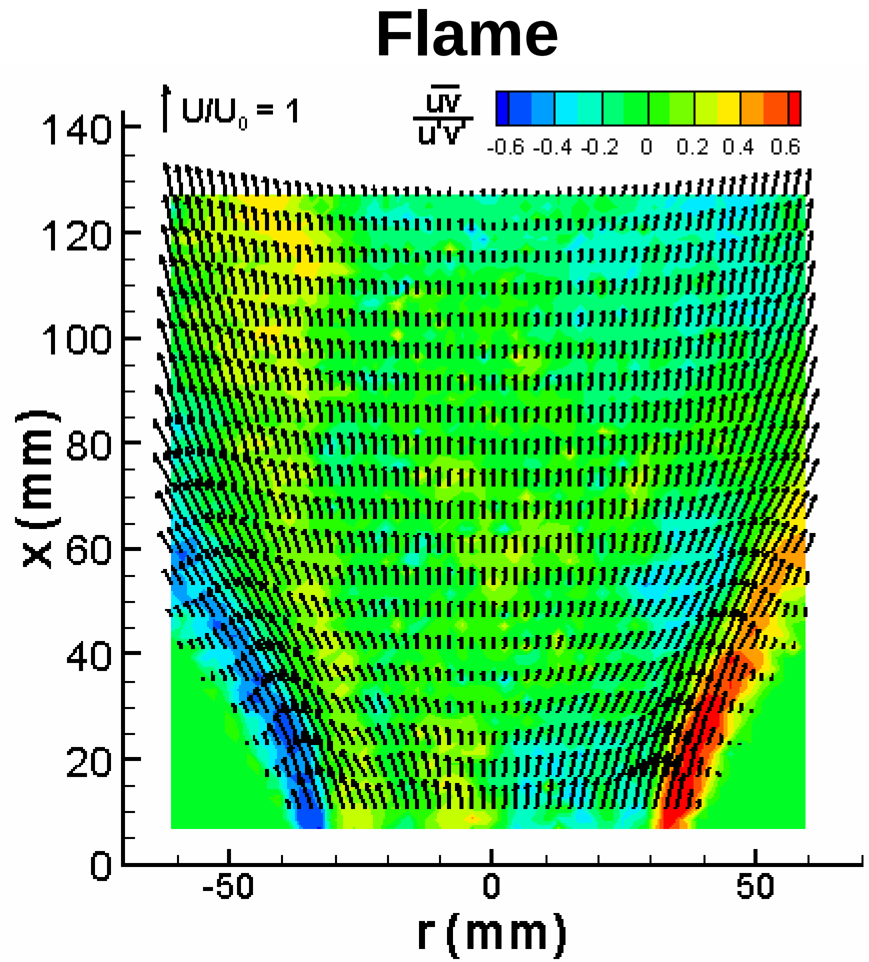


Flame

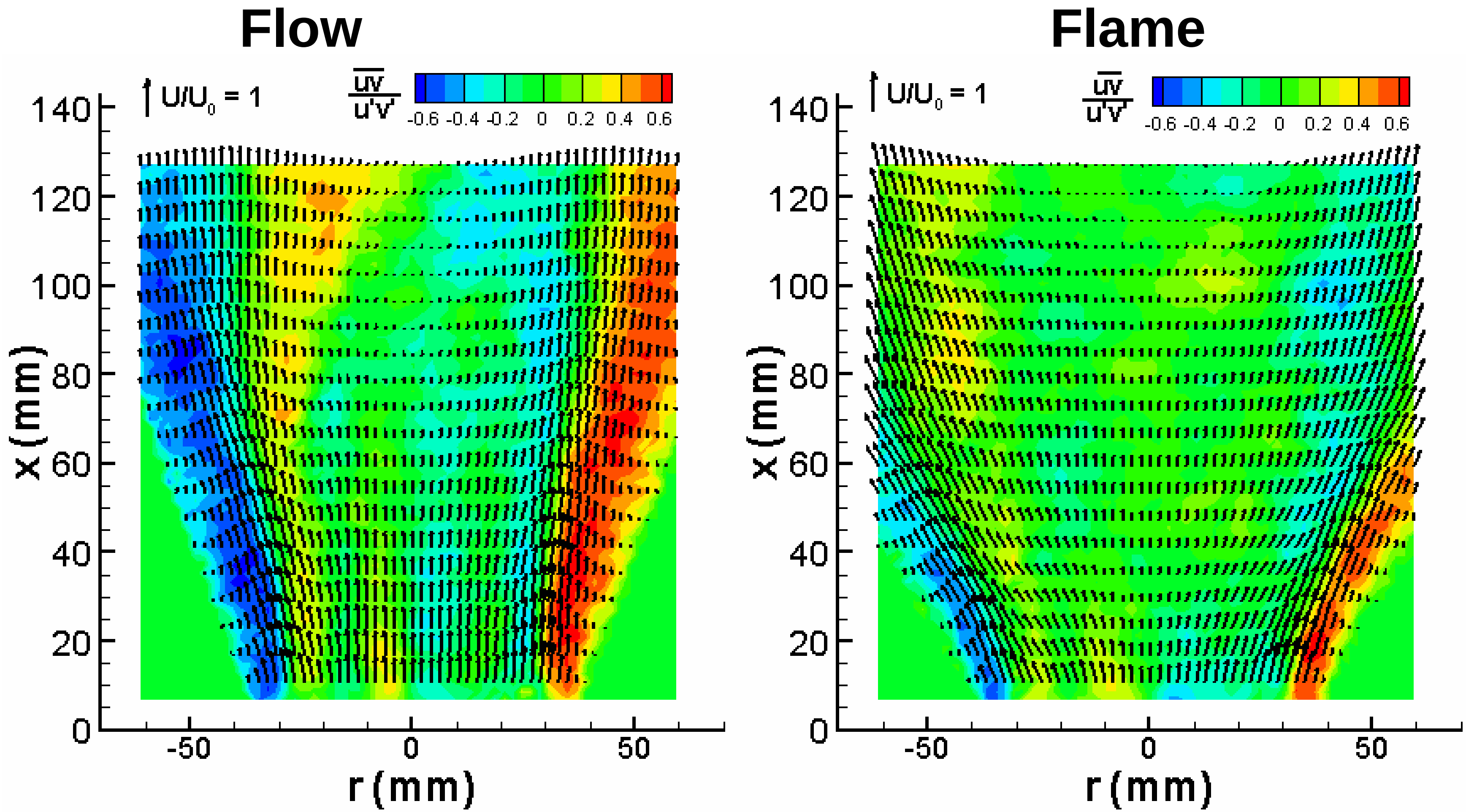


Normalized mean vectors and Reynolds stress at U_0 = 10 m/s

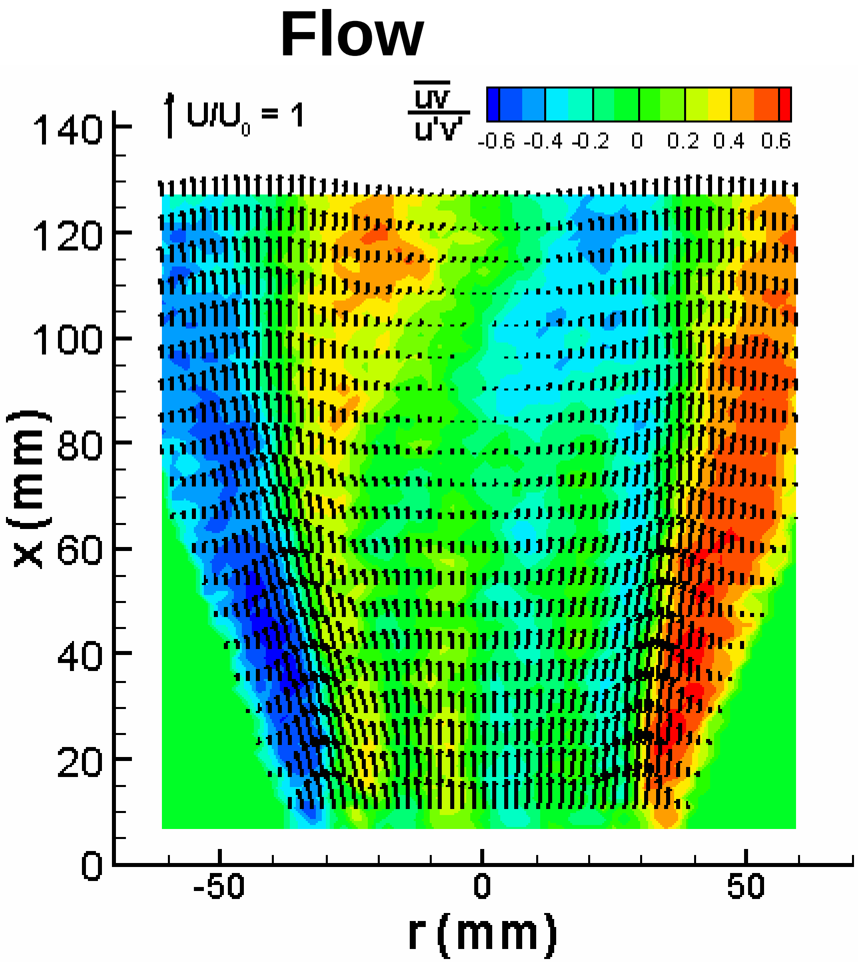


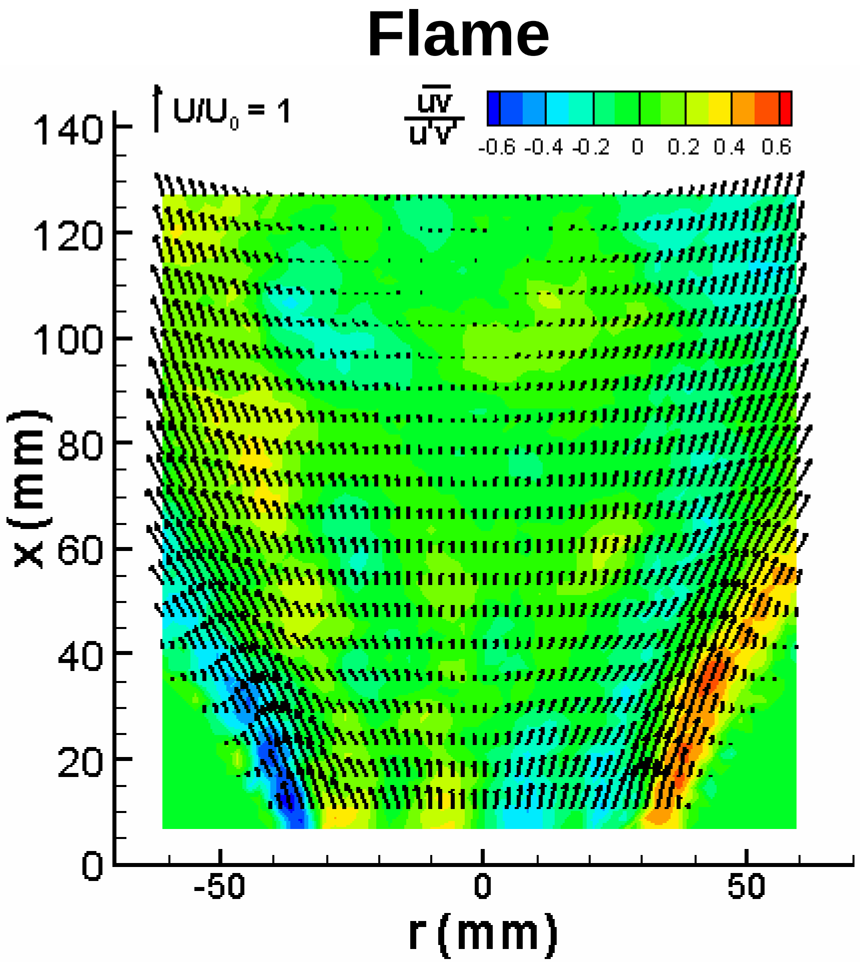


Normalized mean vectors and Reynolds stress at U_0 = 15 m/s

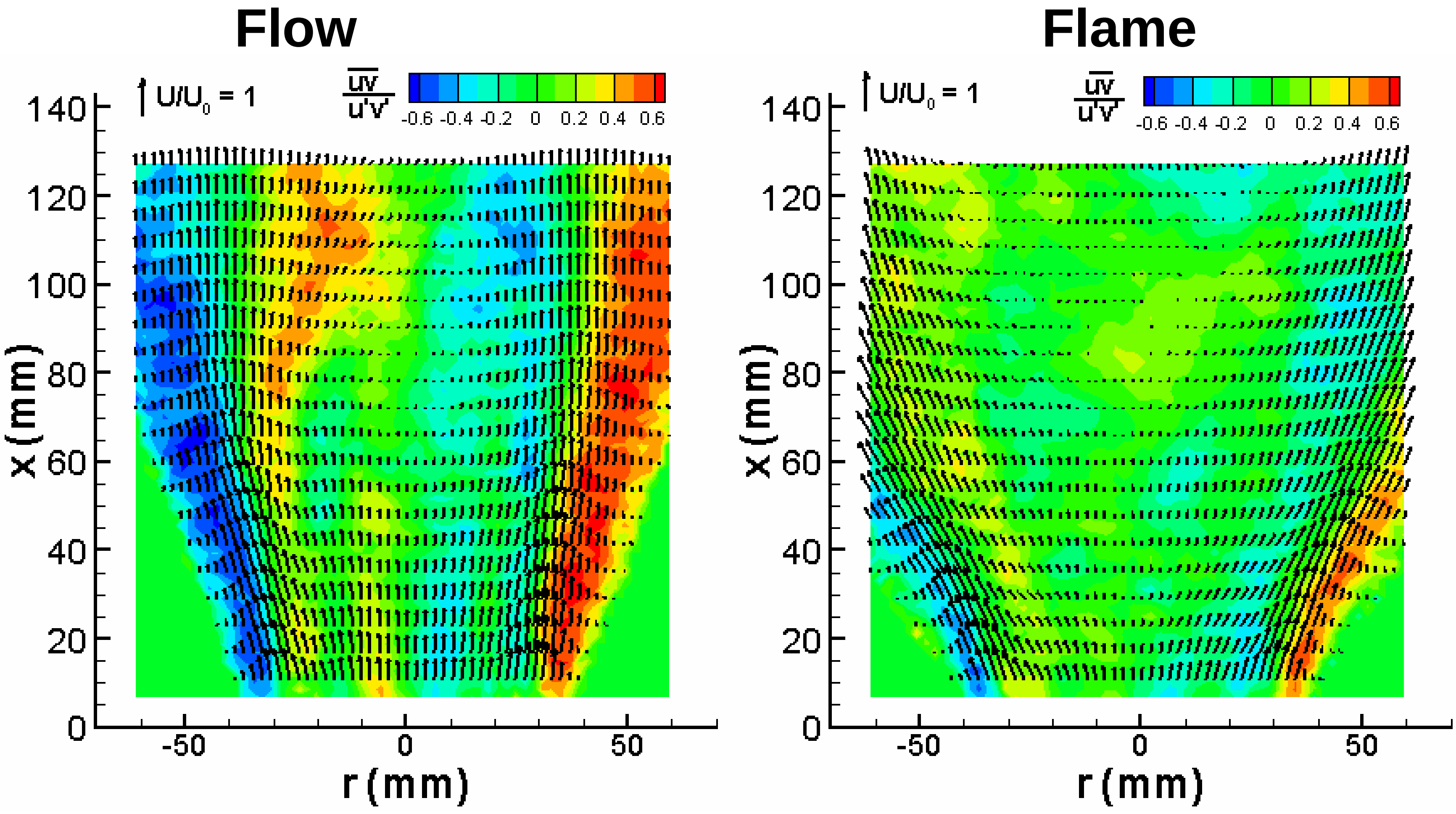


Normalized mean vectors and Reynolds stress at U_0 = 19 m/s



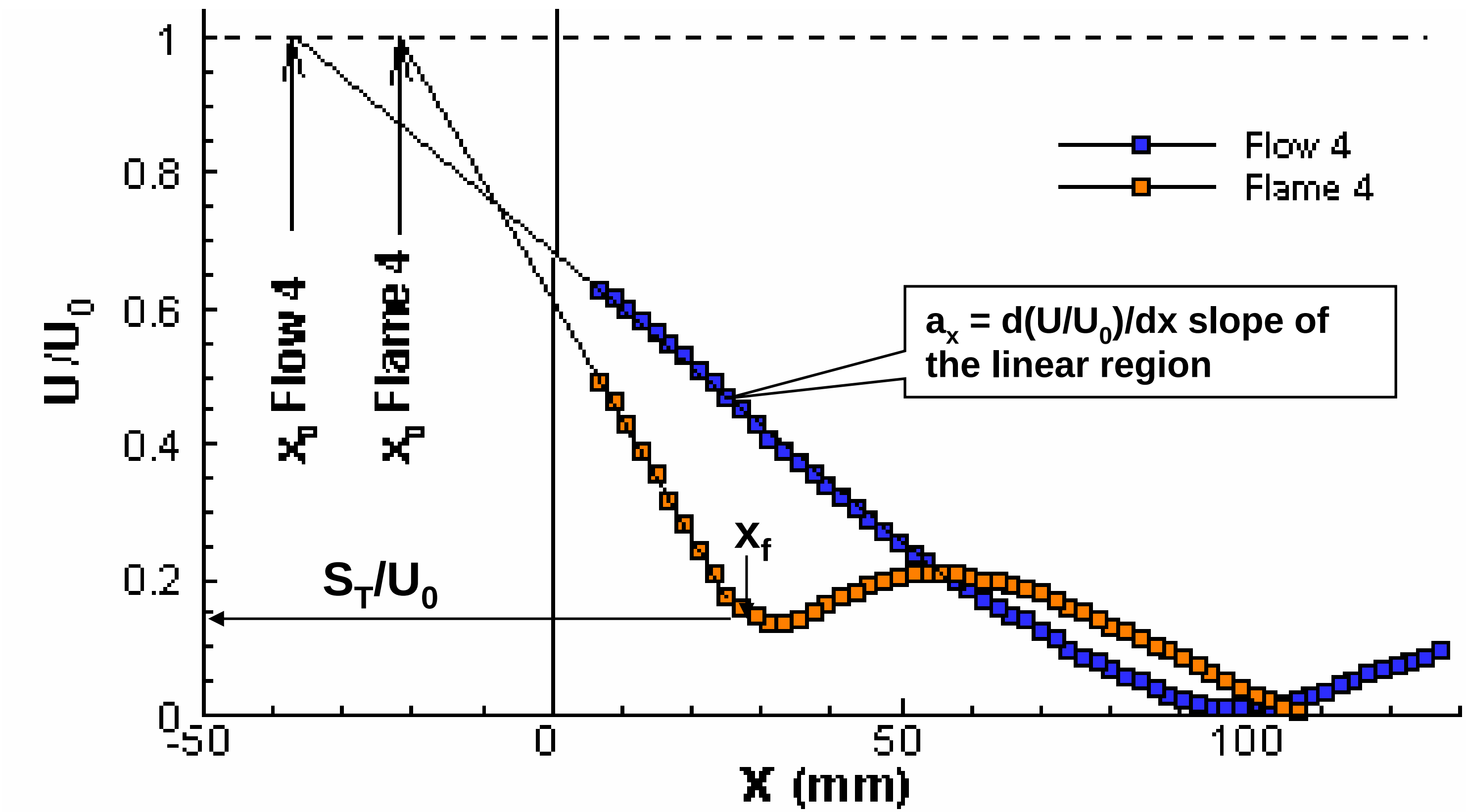


Normalized mean vectors and Reynolds stress at U_0 = 22 m/s

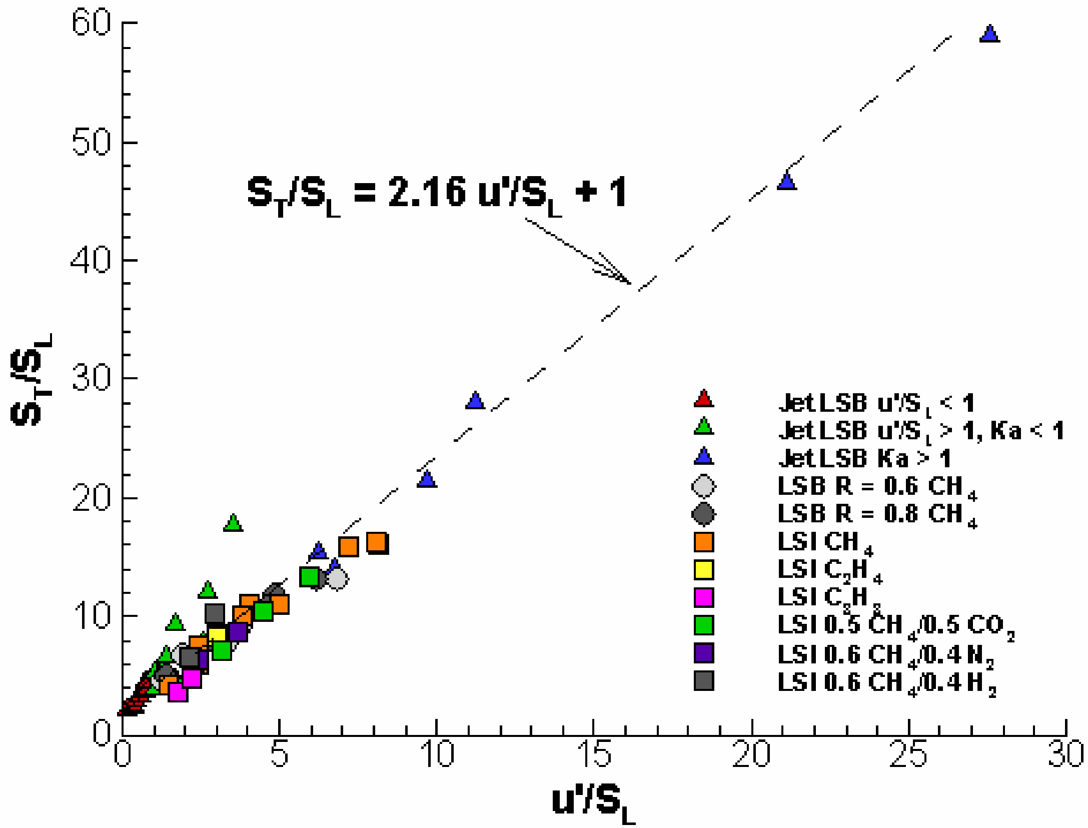


PIV Measures the Parameters that Describe Flame/Flow Coupling in LSI

- **Four parameters deduced from the centerline velocity profile Virtual Origin, x_0, Normalized Axial Divergence Rate, a_x, Flame Position, x_f and Turbulent Flame Speed, S_T**

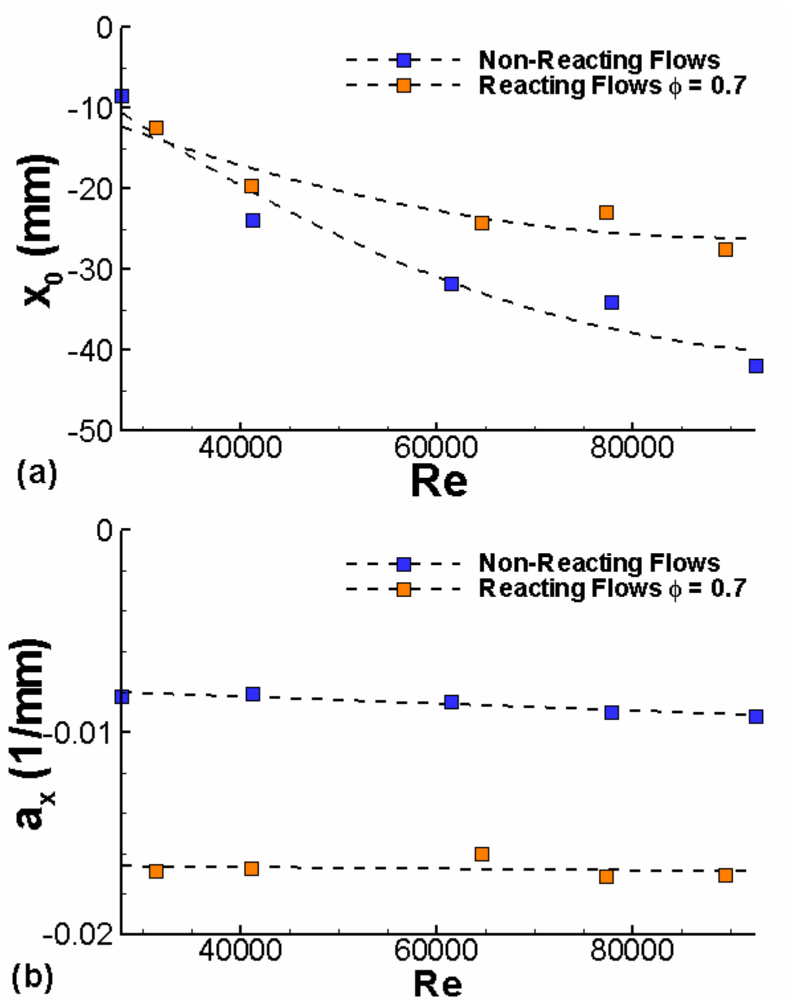


S_T of CH_4, C_3H_8, C_2H_4 and Diluted HC Flames Show Linear Correlation



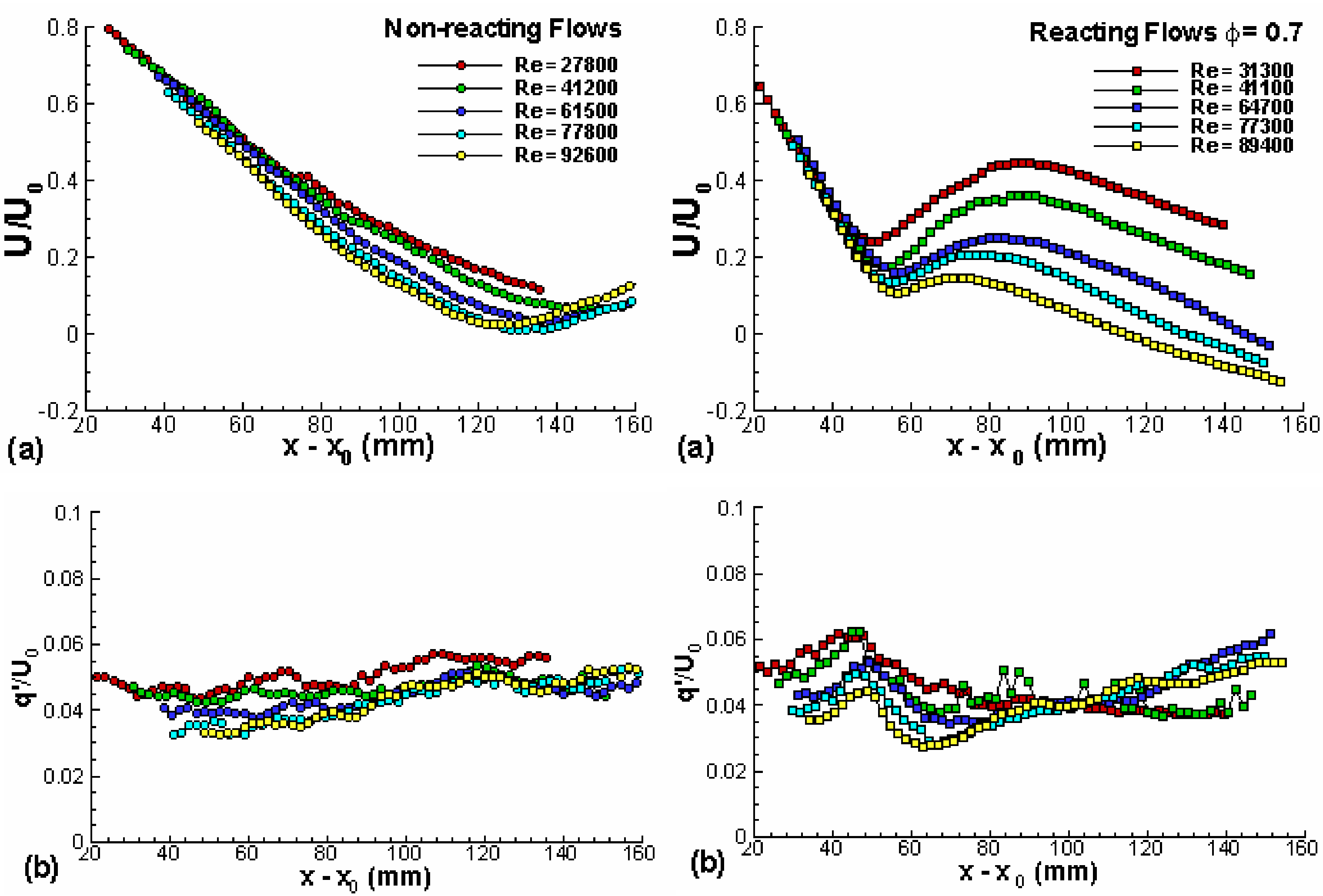
- S_T from LSI flames consistent with those of previous studies
- Linear behavior unique to low-swirl combustion
- Additional data being obtained at higher U_0

Trends of x_0, and a_x with Reynolds Number Indicate Similarity



- **Virtual origin x_0 leveling-off at high Re**
  - **Slight shift of the divergence flow structures into the injector barrel with increasing velocity**
- **Normalized divergence stretch a_x insensitive to Re**
  - **Combustion generates a systematic increase in a_x**
- **Nearfield flow structures have a similar form that is independent of power output**

Similarity in the Nearfield Shown by Normalized Centerline Profiles



Significant Implication of Similarity

- Provides an analytical means to quantify the flame/flow relationship by the use of a_x, U_0, S_T and x_f
  - the axial velocity at x_f is

$$U_o - \frac{dU}{dx}(x_f - x_o) = S_T$$

  - Divide through by U_0 and invoke S_T correlation gives

$$1 - \frac{dU}{dx}\frac{(x_f - x_o)}{U_o} = \frac{S_T}{U_0} = \frac{S_L}{U_0} + \frac{2.16u'}{U_o}$$

invariant due to similarity (i.e. a_x)

asymptote at large U_0

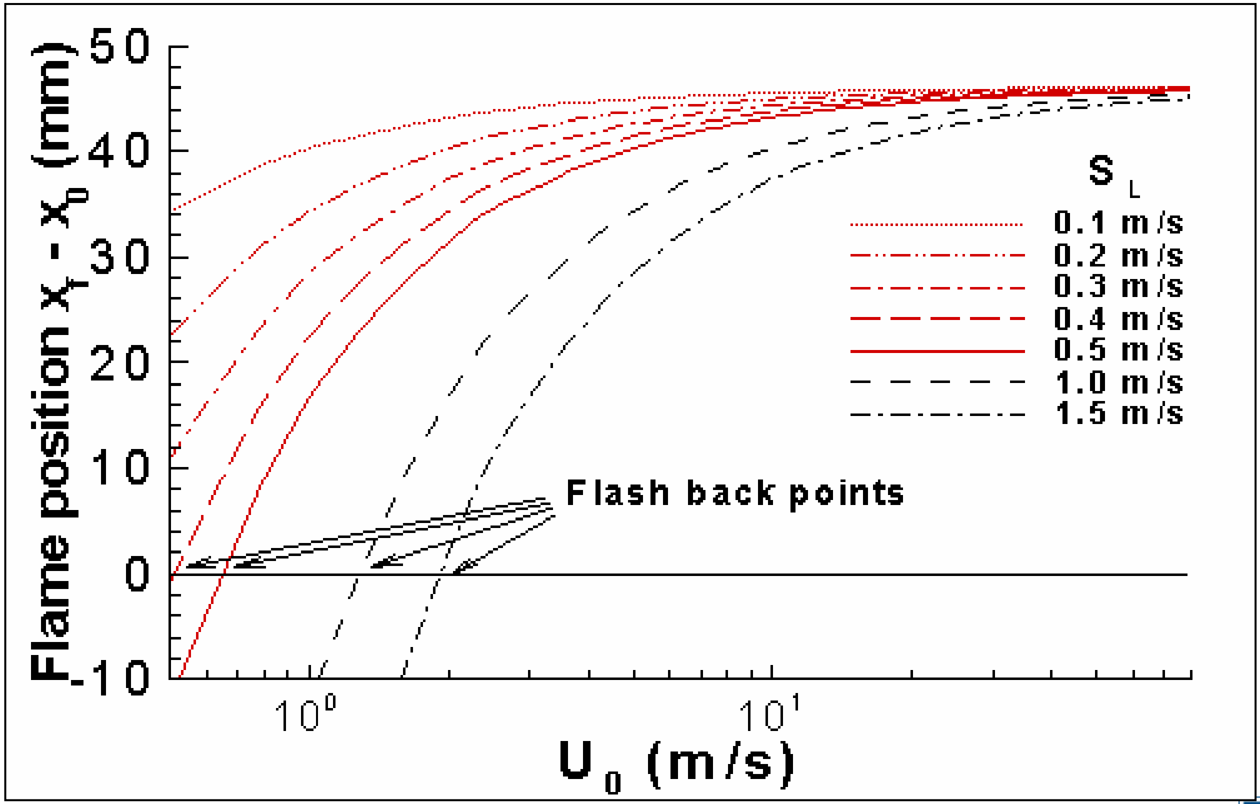
small at large U_0

constant for plate turbulence

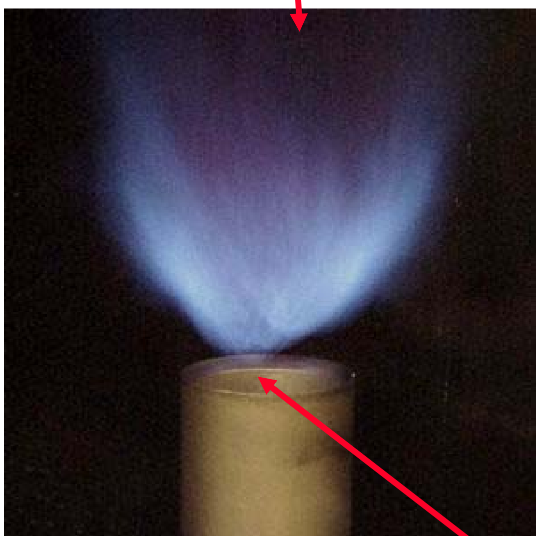
Flowfield similarity and linear S_T correlations explains why flame remains stationary through a wide range of velocities and ϕ

Flashback and Flame Positions Predictable from Analytical Equation

- **Results imply that fuel effects are significant only at low U_0**
  - **Velocity at flash back correlates with S_L**
  - **Flame position independent of S_L at large U_0**



Flashback Considerations for Low-Swirl and High-swirl

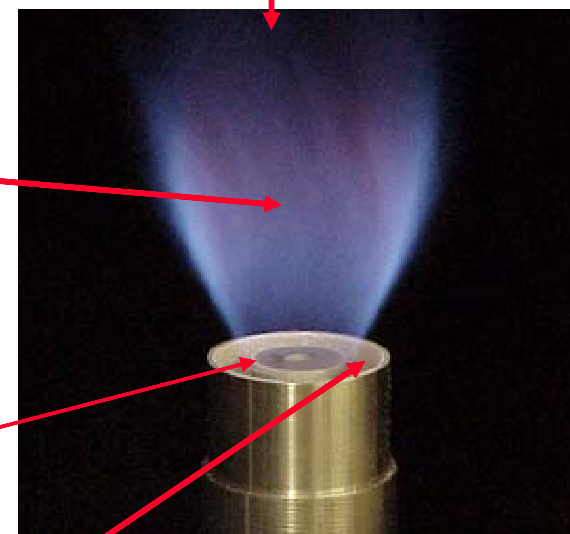


Combustion oscillation flashback

Vortex breakdown flashback due to axial vorticity in recirculation region

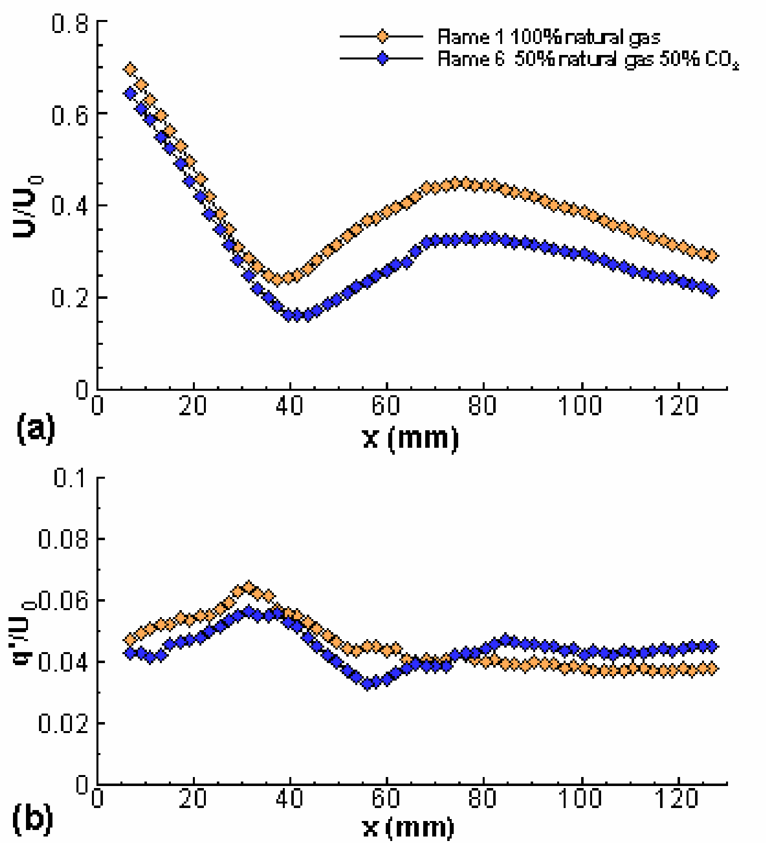
Flashback through hot boundary layer at flame attachment region

Convective flashback – local velocity < S_T



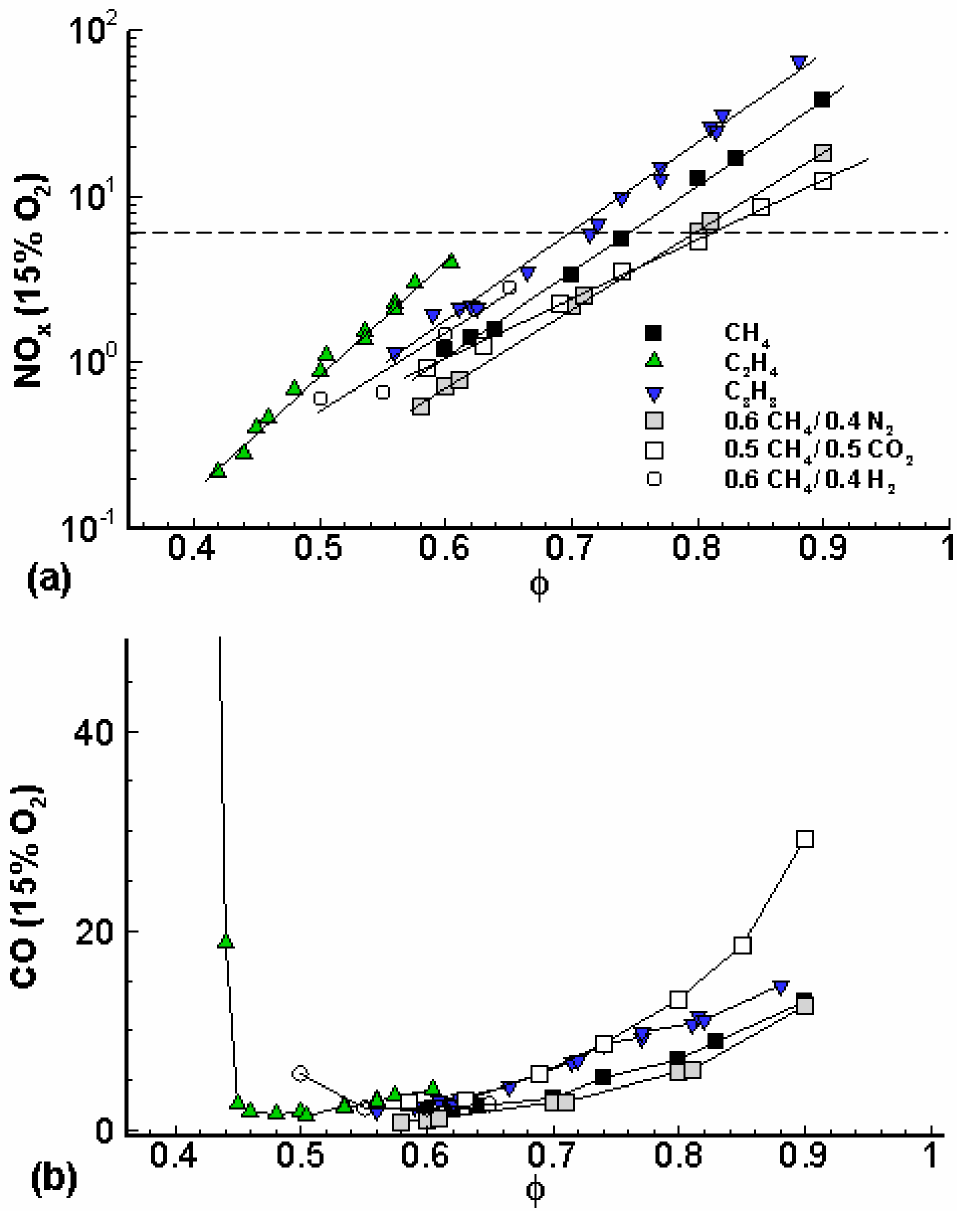
- **LSC analytical model addresses convective flashback**
- **Need studies on LSC vulnerability to combustion oscillation flashback**

Flowfield Features Unaffected by Fuel Type



- Flowfield features of CH_4 and diluted CH_4 flames are the same
- Flame stabilization mechanism not affected by variation in fuel composition
- Slight shift in flame position due to slower burning flame

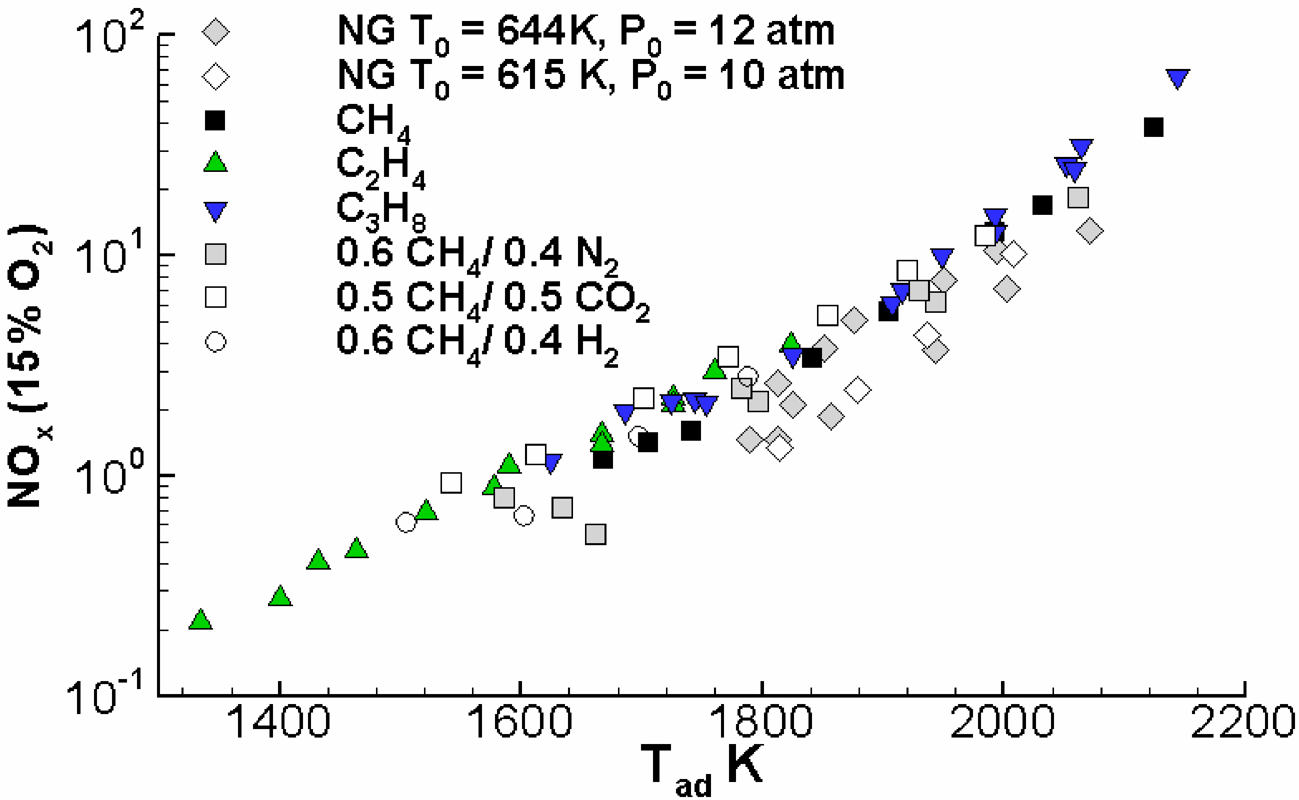
LSI Supports Stable < 5 ppm NO_x Hydrocarbon Flames



- Exponential NO_x dependence on ϕ
- CO emissions within acceptable limits

NO_x Emissions Show Log-linear Dependency on Flame Temperature

- NO_x emissions from STP laboratory experiments consistent with data at gas turbine conditions
- Absence of strong recirculation in LSI may explain the correspondence between laboratory and GT emissions



Preliminary Conclusions on Hydrocarbon Fuel-Flexibility Studies

- **LSI accepts all test fuels including CH_4 diluted with H_2**
- **LSI supports stable < 5 ppm NO_x flames**
- **NO_x emissions scale with adiabatic flame temperature**
  - NO_x emissions from laboratory flames STP consistent with high pressure rig test data at turbine conditions
- **Significant adjustment may not be necessary for current LSI to fire with hydrocarbon fuel blends**
  - **S_T of hydrocarbon and CH_4 flames have same correlation**
- **Recent high T, P rig-tests at Solar Turbines demonstrate firing with fuels from 550 Btu/ft^3 to 1250 Btu/ft^3**

Considerations for Adaptation of LSI to Fuel-Flexible & IGCC Turbines

- **Changes in flame speed correlation will be the 1st order effect**
  - **Turbulent flame speeds for HC fuels have similar correlation as natural gas**
    - **Significant redesigning of swirler may not be necessary**
  - **Turbulent flame speed data for H_2 mixtures are lacking**
    - **Large uncertainties in laminar flame speed data for lean H_2 mixtures**
- **Changes in heat release will be the 2nd order effect**
  - **Changes in LSI flowfield correlates with combustion heat release**
- **LSI swirl rate can be adjusted to accommodate the fuel effects**
  - **Increase or decrease the swirl rate to optimize flame position**